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III

MECHANICAL ASPECTS OF AËRONAUTICS.

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Scope of Paper.

The present paper deals with heavier-than-air machines only. No attempt will be made to describe the present situation in comprehensive detail. The achievements of the past and the present condition of the art of aëroplane design, construction and operation must, for the most part, be assumed. The purpose of the paper will be rather to point out the more important problems pressing for solution, the elements in the broad problem of aëronautics which we may reasonably hope to improve, and so far as the author is able, to indicate the directions in which improvement may be sought.

The subject will be considered under the following general heads:

Structure of Aëroplane.
Power Plant.
Propulsion.

Structure of Aëroplane.

As a problem in engineering design the aëroplane presents the following features.

Required a structure coherent as a whole, provided with large flat or gently curved surfaces for realizing the necessary support, with suitable accommodation for the personnel, and with suitable structures for supporting a prime mover and for receiving the thrust of a propeller, fitted also with suitable auxiliary guiding surfaces for control in the air, and with suitable strength in all its parts to resist with a reasonable margin of safety the stresses to which it will be subject in the accidents of aërial navigation.

In its essence, however, the aëroplane is a wing or a combination of wings fitted with one or more engines and propellers.

The chief structural problems are therefore concerned with

(1) The design and construction of the wing.

(2) The design and construction of the members necessary and sufficient to join the wings together into a coherent structure suited to the purposes in view.

The wing again presents two problems. The *surface* and the *framework* necessary to give form and strength to the whole.

The amount of surface to be provided is dependent, according to well known laws, on the weight to be supported and on the speed at which support is to be realized. In the outlook ahead the insistent demand will be for the largest practicable size. We may therefore put the question bluntly, what is the largest attainable size, what elements tend to limit size and how may we hope to remove, in some measure, the effect of these limitations.

If we consider a series or family of aëroplane structures, homologous in all dimensions and differing only in size, we shall evidently find a ratio of surface to weight decreasing with increasing dimensions. The weights will increase as the cube of the linear dimension, the surfaces as the square, and hence the ratio of surface to weight will vary as the inverse ratio of increasing dimension. It follows that for such a series of structures the weight of the structure itself will tend to absorb an increasing part of the total weight which the surface should sustain at any given speed, and with corresponding reduction in the surplus lifting capacity available for power plant, crew, armament, express freight, etc.

Let x denote any linear dimension of the plane.

A the area.

W_1 the weight of the plane and auxiliary structures.

Then for a family of structures such as are here considered we shall have

$$A = Bx^2,$$

$$W_1 = Cx^3,$$

where B and C are two coefficients connecting respectively area with the square of x and weight with the cube.

At any given speed let the relation of total lifting capacity to area be expressed by the ratio m. Then if W = total lifting capacity we have

$$W = mA = mBx^2.$$

Denote the net lifting capacity by y. Then we shall have

$$y = W - W_1 = mBx^2 - Cx^3,$$

$$\frac{dy}{dx} = 2mBx - 3Cx^2 = 0, \qquad 1$$

$$x = \frac{2}{3}\frac{mB}{C},$$

and

$$y_m = \frac{4}{27}\frac{m^3B^3}{C^2}. \qquad 2$$

For such a series of structures therefore the maximum net lifting capacity will be given by a size determined by the value of x in equation (1) and the actual maximum net weight will be as in equation (2). For larger sizes of structure the weight required in the structure itself will increase more rapidly than the carrying capacity depending on area, and hence the net lifting power will decrease. It results furthermore that for such a family of structures there will be some size for which, all at a given uniform speed, the net carrying capacity will be zero, a size for which the total lifting capacity at the stated speed will be only just able to carry the weight of the structure itself.

We may now ask two important questions.

(1) What measures must be taken, in such a series of structures, to increase the maximum net carrying capacity?

(2) To what extent do these conclusions apply to a series of actual aëroplanes of continuously increasing wing surface?

Regarding question (1) the form of the expression for y_m shows that it varies directly with m^3, directly with B^3 and inversely with C^2. We must therefore seek to increase m and B and decrease C. We cannot hope to affect the value of B, the relation of area to linear dimension. We may, however, increase m by increasing the speed and decrease C by improved design or by developing materials stronger for a given weight than those now employed.

Regarding question (2) we may state the problem thus. For a series of aëroplanes of increasing area, how closely will the increase in weight vary with the $3/2$ power of the rate of area increase?

Broadly speaking the relation seems to hold within a significant degree of approximation. The weight of skin covering itself will increase as the surface. All structures subjected to cross breaking and in general all elements which tend to constitute the structure as a whole into a truss or girder will, except as the character of the design may change increase in their own linear dimension nearly with the overall increase in linear dimension, and hence in weight nearly as the cube of the linear dimension or with the $3/2$ power of the surface. Time does not permit any detailed analysis of this important problem, but broadly speaking we may expect that in a series of aëroplanes of the increasing area the weight will increase somewhat more rapidly than the area but somewhat less rapidly than the $3/2$ power of the area.

The practical question is this. To what degree of approximation in a series of aëroplane structures will the structural weight vary with the $3/2$ power of the area of wing? We know that for a given speed, wing area and gross weight vary nearly in direct linear ratio. Hence if the structural weight increases more rapidly than the area but somewhat more slowly than with the $3/2$ power, it is obvious that for any given speed there will be some area which will insure the maximum net lifting capacity and beyond this area the next lifting capacity will decrease.

Actual experience seems to indicate an increase in weight related to wing area according to an index lying between 1 and $3/2$ and varying somewhat irregularly according to the changing type of construction with increasing size. Hence we may conclude that for a given speed continued increase in size of wing alone will not insure indefinite increase in the net carrying capacity, but that instead there will be some area for which the net carrying capacity may be expected to reach a maximum, after which further increase in size at the same speed will involve a loss in carrying capacity.

It follows again that in order to increase carrying capacity the following steps are indicated.

1. Improvement in the elements of design and in the materials of construction.

2. The selection of such a size of wing as shall insure for the type of design and for such wing as an element in the structure as a whole, the maximum net carrying capacity.

3. Increase in speed to the upper limit practically attainable.

4. Increase in number of planes.

Recent experimental work with three, four and five planes seems to point to the multiple plane as perhaps the most immediate means of increasing carrying capacity. Or in other words, given the limitations imposed by structural materials and the upper limit of speed considered practicable and expedient, multiple planes seem to be the immediately remaining recourse for further advance in net carrying capacity.

Passing now briefly to the actual materials available, we may make a classification as follows.

Surface material (cotton or linen duck fabric).

Wing skeleton or structure—wood (spruce and mahogany), steel.

Struts and braces connecting wings in multiple—wood (spruce and mahogany), steel or special alloys.

Body or boat material: Framing: wood or steel. Covering: wood veneer or sheet metal.

Ties for serving as tension members in connecting wings to body or in multiple: steel wire, single or laid up in cable.

Fastenings: drop forgings, sheet steel, bronze.

The two fundamental problems are:

1. The development of materials furnishing more strength for the same weight.

2. The better disposition of the materials which we now have.

Passing the above classes of materials briefly in review, we may note as follows. There does not seem to be anything immediately in sight better than the materials now used for surfaces. With suitable treatment (usually coatings of celluloid dissolved in acetone with varnish finish) the material stretches tight, takes a smooth surface and has sufficient strength to support itself between the supporting ribs.

The surface does not form a large fraction of the total weight and saving here is not relatively as important as in the framework.

The substitution of metal for wood in the framing has long since attracted the serious attention of aëronautic engineers, and in certain recent designs the problem has been worked out with apparently a high degree of success. These results indicate the probability of an increasing use of steel for parts which have hitherto usually been made of wood. The peculiar qualities of stiffness and resilience combined with readiness of shaping and forming have combined to make wood broadly speaking the standard material for the skeleton or framing of the wings and body. It seems, however, a foregone conclusion that some parts now made of wood might with advantage be made of the best modern alloys combining strength with light weight. The extent to which this can be wisely done can only be determined by trial, but it seems probable that perhaps important savings in weight may be made by a judicious substitution of metal in certain elements of the structure.

The outlook for the future calls for new and improved metal alloys with certain of the physical characteristics of wood, as nearly as may be realized, and with proper form and proportion securing the development of the same strength with saving in weight.

The use of steel wire and cable for ties is standard and practically universal. These elements form a relatively small part of the total structural weight. It seems hard to imagine material superior to the best modern alloy steel wire, but there seems no reason for assuming that such material represents the last word in the wire-makers' art and if we may anticipate new and improved steel or bronze alloys, such material will provide the necessary tension elements with some slight saving in weight.

Fastenings have been made the subject of much study, experimental and otherwise, and the field is still open for further improvement. Here again the total weight is relatively small, but there may well be a chance to save something in weight and at the same time add to the security and integrity of the design as a whole.

Broadly speaking, there seems small ground for anticipating any profound change in the near future in the schedule of materials best available for the designer of aëroplane structures. Gradual advance there will be, and with it the designer of such structures must be quick to seize such advantage as he may.

Regarding a better disposition of the materials we now have, it may be assumed that there is a more promising field. It is peculiarly a field which must be worked in an experimental way, and while much has already been accomplished there is still room for further saving in weight through a better disposition of the elements of structure employed.

The problem is broadly; given an aëroplane structure exposed to the hazards of flight and involving baffling head winds, gusts, forced severe banking, diving, quick turning about various axes of motion and all in various combination, required a structure which shall present a substantially uniform factor of safety relative to the extreme stress, in any and all directions, to which it may be subjected.

This is obviously not a problem to be solved by theoretical methods or over the drawing board alone or even chiefly. It is distinctively a problem to be worked out primarily by experience supplemented by experiment, which is, after all, only experience realized under control conditions.

One of the future developments which should not be lost sight of lies this way and should comprise comprehensive studies of the combinations of structural elements available, always with the view of realizing more efficient results; that is, a more equable distribution of the strength realized with a corresponding saving in weight.

The problem of weight economy is vital in the science and art of aëronautics, and the possibilities of advance through a well-ordered program of experimental investigation on full sized forms should not be lost sight of.

POWER PLANT.

We pass next to the subject of the aëroplane power plant. We here meet the following principal problems.

1. The problem of fuel.
2. The problem of carburetion or preparation for combustion.
3. The thermodynamic problem of the transformation of the heat energy into mechanical work.

4. The problem of auxiliaries.
5. The problem of construction.

Gasoline stands preëminent as the standard fuel for aëroplane service. The chief objection is its high price. This will operate to produce a serious limitation in the economic application of the aëroplane and one of the most important problems with special reference to an extension of economic use is the development of prime movers capable of using cheaper grades of fuel. It will not be without interest, at this point, to note the fuel cost per ton mile for aëroplane service as compared with the same item for railroad and for marine transport. If we take an aëroplane with say 130 h.p. carrying 300 pounds of cargo at a speed of 60 m.h. we shall find with gasoline at 20 cents per gallon a fuel cost of about 30 cents per ton mile. This will compare with about 1/10 cent in the case of a heavy freight train and with about 1/40 cent in the case of say a 10,000 ton steamer. The fuel cost for merely carrying dead weight may therefore readily be from 300 to 1200 times as great as for railroad or marine carriage. This unfavorable relation between the economics of the fuel cost for aërial and for marine transport arises from certain relations which develop in the two cases between net cargo weight and gross weight, and between horsepower and gross weight.

Thus for the ship the net cargo weight may be, for moderate speeds, as high as 50 per cent. of the gross weight, while for the aëroplane as noted, it would be about 12 per cent. Again the ship requires for a speed of say 15 miles per hour, a horsepower of 5,000 or less, or not exceeding 1 h.p. for 4,500 pounds gross weight while the aëroplane requires something of the order of 1 h.p. for 15 to 20 lbs. gross weight. Again the fuel for the aëroplane engine costs from 5 to 8 times as much per horsepower hour developed as for the ship prime mover.

While the fuel represents by no means the whole cost it is an important item and it is clear that so long as the aëronautic engineer is limited to gasoline fuel the economic uses of the aëroplane must be seriously handicapped.

There are other fuels cheaper in character and developed to a point where they are satisfactorily employed in certain grades of internal combustion service, notably kerosene and distillate, and cheapest of all, crude oil which is used in engines of the Diesel type. The demands of aëronautic service are, however, insistent in regard to the holding of engine and machinery weights to the minimum and any attempt to use fuels other than gasoline must reckon with the possibility of increased weight. This limitation will apparently, at least under existing design conditions, rule out the Diesel engine from consideration.

With existing conditions of design and operation there seems to be nothing in sight as an immediate substitute for gasoline, and we cannot well see in what direction to turn for the ultimate solution of this problem. It is, however, none the less real and the economic extension of the aëroplane will depend in large measure upon the success or failure of efforts directed toward the development of a cheaper fuel.

Passing now to the problem of the carburetor only the briefest reference can be made to the principal details of this problem.

The primary function of the carburetor may be defined as the mixing of the gasoline in a finely divided state with the air necessary for combustion. Following this, on its way to the cylinder and on entering the cylinder, the liquid fuel becomes rapidly vaporized and ready for compression and ignition. The fundamental requirements are the following:

1. Fine subdivision of the liquid fuel.
2. A uniform or nearly uniform mixture by proportion of gasoline to air at varying motor speeds.

For aëroplane service, there should be, in addition, some adjustment, either automatic or manual, with reference to altitude and the consequent varying density of the air.

The function of the carburetor may be viewed under two heads.

1. Reliability.
2. Economy.

For aëroplane service a carburetor giving a nearly uniform mixture over a wide range of operating conditions is of special importance from the standpoint of reliability. When the life of the aëronaut may well depend on the degree of reliability with which the carburetor furnishes a nearly uniform mixture suited for ready ignition, the importance of this phase of the problem is apparent without further emphasis.

The best of present carburetors realize these conditions in high degree. The principal points still open for improvement are perhaps the following:

1. Improved means for atomizing the liquid fuel, looking especially toward the finest attainable degree of subdivision. This will aid both economy and reliability.

2. Improved means for covering a wide range of atmospheric conditions as regards density, temperature and humidity, and with a wide range of power developed under any combination of these conditions.

3. Improved means for atomizing the gasoline with the minimum drop in pressure through the carburetor. This will aid in decreasing the back pressure and will increase the net power developed per cycle.

Improvement in the carburetor is primarily dependant on experience. The interaction of the various controlling factors is so complex in character that cut and try methods based on the intelligent application of underlying principles seem to promise the most fruitful results in the improvement of this element of the internal combustion prime mover. The field is open and we may look confidently to the future to provide a standard form of carburetor which will secure the highest practicable results over the widest range of operating conditions.

We turn next to the thermodynamic aspect of the problem.

Under this head I shall only refer briefly to the character of thermodynamic cycle employed. As well known, the cycle at present universally employed is that based on the constant volume—adiabatic ideal. There remain open the constant pressure-adiabatic cycle and the constant temperature-adiabatic or Carnot cycle, or some combination of these.

The Diesel engine uses a cycle more or less intermediate between the latter two.

The constant pressure-adiabatic cycle has long been the ideal of engineers with special reference to sustained crank effort and the elimination of the explosive shock characteristic of the constant volume-adiabatic cycle. Thus far, however, structural and operative difficulties in various details of the process have prevented the wide use of this cycle. It is, however, just now the subject of special investigation at the hands of engineers of insight and resource and it may well be that the near future will open up to the aëronautic engineer this cycle for practical use in engines for aëroplane service. If engines operating on this cycle can be made a success in the operative sense while at the same time keeping the weights down to the limits reached with the type now employed, we may anticipate a wide field of usefulness for this cycle.

Under the head of auxiliaries the chief functions are ignition, cooling and lubrication. To these we may perhaps add, as rapidly approaching the status of common acceptance, some form of starting motor or device with wireless outfit, especially for military purposes.

Under ignition the insistent requirement is reliability, commonly assured, so far as auxiliary equipment is concerned, by magneto installation in duplicate.

Cooling is normally by water, except in the rotating type of engine, where air cooling prevails. The principal problems here relate to methods of circulating and cooling the water, security of joints and connections, minimizing loss of water by boiling and assurance of adequate supply for long life in air without going to needless excess weight in water carried.

The principal problems presented by lubrication are reliability and simplicity of means employed, usually some form of pressure or positive supply system.

Further references to problems presented by auxiliary equipment are more conveniently made under the next following head.

Under the general head of construction, time will only permit of brief reference to the following topics:

Materials.
Design.
Fabrication.

The materials employed are chiefly cast and wrought steel, cast iron for some few parts, aluminum and bronze. In order to reduce weights to a minimum forged steel is used for the cylinders or cylinder liners and generally for all parts receiving or carrying the direct load. Further progress here will wait on the skill of the metallurgist in furnishing steels of higher physical properties than those now available. Broadly speaking, the present aëronautic engine, in the most refined designs, exhibits a very near approach to the practicable limit with the materials at present available and further saving in weight must depend chiefly on the work of the metallurgist in developing new and improved materials for use.

The chief outstanding problems in the design of aëronautic engines are those dealing with the most effective disposition of the available materials of construction, and with the forms, proportions, arrangements and assemblage of the elements in such manner as shall secure the highest practicable degree of reliability of operation.

In the disposition of the materials with reference to the strength and stiffness required, the fundamental and insistent demand is the saving of weight. This problem is one to be studied partly by the application of mechanics and general engineering principles, and partly by experience. In any given engine there is no question but that there is a certain amount of redundant weight. The problem is to locate it. While, as already noted, the best of modern designs represent apparently a close approach to the ultimate attainable with existing materials, nevertheless the field of design with reference to further refinement is still open and will doubtless well repay further study. This road marks clearly one of the ways whereby future progress and improvement must come.

The principal problems dealing with improved reliability and with length of operative life may be enumerated as follows:

1. Oiling system and lubrication generally.
2. Means for securing all pipes and conduits, whether for oil, water or electric wiring, in such manner that jar and vibration cannot cause their rupture or separation at joints.
3. The reduction of vibration to a minimum by the careful balancing of rotating and reciprocating parts so far as practicable.
4. Adequate bearing surfaces especially for all principal parts, so that with a reasonable supply of lubricant there need never be danger of cutting or abrasion.
5. Adequate crank shaft size and adequate crank shaft bearings,

both in surface and in number, so that the shaft may be shielded from alternating flexure, a condition certain to result in early rupture.

6. Simplicity and directness of operation the valve gear.
7. Simplicity and directness of drive for all auxiliary machinery such as magneto, water and oil pumps.

In connection with the general problem of lubrication, one of the great problems, perhaps the one most important problem in connection with the aëroplane prime mover, relates to the possibility of developing metals of such physical properties or relations that they will operate in sliding relation without serious abrasion and without the need of constant lubrication, at least in terms of the practice found necessary with the materials now employed. Whether any such metals in pairs can be developed or whether the surfaces of metals will admit of treatment in any way which will reduce in marked degree the amount of lubrication required, is of course an open question; but the march of scientific and engineering progress is marked with many discoveries and developments seemingly far more remote from possibility than is this. In any event it is a field well worthy the most careful investigation, not alone for its importance in connection with aëronautic prime movers but also for the far-reaching influence which it would have throughout the whole field of engineering design. It represents moreover a serious need in the case of the aëronautic prime mover with reference to increased safety, simplicity and decreased cost of operation.

These problems, and others allied, all offer inviting fields for the research engineer, the designer and the inventor. It is, furthermore, difficult to overestimate their importance. Thus the rupture of a small oil pipe, perhaps ⅛ inch diameter, due to vibration resulting in a crystallization of the metal at a point of attachment, might result in the failure of lubricant to reach some important element of the engine, as a consequence of which the bearing heats, abrades, perhaps seizes, the engine stops and possibly disaster comes swiftly as a consequence. When safety of life may depend on continuous operation of the engine, no item or element bearing on reliability is too small to receive the most serious and earnest efforts on the part of those responsible for the design and construction of the prime mover.

It seems appropriate to note at this point, that until the margin of uncertainty or of unreliability is reduced far below where it now stands, the navigation of the air will be closed to the great mass of people who will prefer the safer if somewhat less thrilling mode by way of the solid earth or the water-borne boat.

PROPULSION.

The screw propeller has been universally adopted as the means for transforming the work developed by the prime mover into propulsive work.

In spite of its simple form the operation of the propeller depends on an astonishingly large number of variables, interrelated in complex and baffling ways, and thus far transcending all effort to bring them into practicable expression through the application of aërodynamic theory. The chief variables or conditions thus entering into the operation of a propeller may be listed as follows:

(*a*) Characteristics of the propeller as a geometrical body.
    (1) The diameter or general determining dimension.
    (2) The pitch of the helicoidal surface employed for the driving face. This may have two different modes of specification, viz.:
        (*a*) The single value of the pitch if uniform, or the mean value if variable.
        (*b*) The distribution of values if variable.
    (3) The form of the contour bounding the blade or helicoidal surface employed.
    (4) The area of the blade on the driving face.
    (5) The cross section or thickness of the blade. This may have two mode of specification, viz.:
        (*a*) Areas of cross sections and their distribution radially.
        (*b*) Forms of cross sections.
    (6) The character and finish of the blade surfaces.
    (7) The form and dimensions of the hub or central body carrying the blades.

(*b*) The characteristics of the adjacent structures such as parts of the aëroplane. These will influence the flow of air to and from the propeller and will thus affect the force reactions resulting from its operation under any stated set of conditions. These may be primarily specified by
  (1) Dimension and form.
  (2) Location with regard to propeller.
(*c*) The characteristics of the medium.
  (1) Density.
  (2) Viscosity.
  (3) Character and extent of turbulence or departure from homogeneous conditions.
(*d*) The characteristics of operation.
  (1) Speed of translation or speed of advance.
  (2) Speed of rotation.

We have thus, without going too far into detail, some 14 variables or conditions, any one of which may exercise an important influence on the results realized from the propeller.

For many purposes and by way of approximate working formulæ, the operation of the propeller is related through empirical coefficients to the three most important of the above listed set of conditions; namely, diameter, pitch and the slip, which is directly expressible in terms of the relation between the speed of advance and the speed of rotation.

Aside from such approximate formulæ, in which the values of the coefficients drawn from experience must be so selected as to care for all variables other than the four directly represented, there seems to be no recourse save either in direct full size experimental investigation, or in model investigation. The limitations of full size experimental investigation are evident, and aëronautic engineers, following the lead of the naval architect, have turned to model experiments as furnishing the most hopeful means of dealing with the problem of the screw propeller.

The use of models presupposes the application of a law or principle of kinematic similitude, and regarding which it is unnecessary to speak in detail on this occasion. It will aid, however, in clarifying our present view to state the underlying assumption as follows.

The existence of a law of kinematic similitude assumes that for any given set of operating conditions for the full-sized body there will correspond a determinable set of conditions for the model and that the results realized for the model may be transformed into the results to be anticipated from the full-sized body by the application of determinable ratios which will be some known function of the relation between the two sets of conditions.

It should be noted further that this relation assumes that *all* of the conditions which may affect the result in question admit of definite expression in terms of mechanics and of definite numerical measurement in specific cases. This is not always possible especially with such factors as surface roughness or degree of turbulence.

Again the special conditions which are required for the model may be inconvenient or even impracticable as regards experimental realization.

These various conditions prevail in the case of air propellers. It is well known that we are only able to realize a practicable application of the law by neglecting the influence of the viscosity of the medium. This of itself, with the air propeller working in an indefinite medium and under loads and speeds which would permit the neglect of the influence due to the compressibility of the air and of the distortion due to thrust and centrifugal force, would make all speeds corresponding. This is equivalent to a reduction of the equation for the thrust of a propeller to the form

$$T = KD^2v^2.$$

Hence with such a relation the model may be run at any speed with the same percentage slip as for the full-sized propeller, and from the observed value of the thrust we may derive the factor K. The constant thus determined should then serve for any diameter so long as the shape and slip remain the same as for the experimental conditions.

If, however, allowance is to be made for compressibility and for distortion due to force loading, theory indicates, as is well known, that the tip speeds of both model and full-sized propeller should be the same.

The form of corresponding speed relation usually adopted for air propellers is in accordance with these indications. There remains, however, a margin of uncertainty regarding the influence due to the neglected viscosity and also a query as to the amount of error which would be introduced by using lower tip speeds for the model than for the full-sized propellers.

These two queries therefore stand out, representing two problems which press for solution and which lie at the foundation of the investigation of air propeller operation through the use of reduced size models.

We must therefore admit that the application of the law of kinematic similitude, in the form commonly employed, to experimental research on air propellers by means of reduced models, lacks full authority in rational theory, and as a result the real justification must come from experience. This means that the tests on models and their interpretation in terms of full-sized propellers must rest ultimately on carefully determined results given by the coresponding full-sized propeller. This does not imply, however, that all model measurements need to be checked by corresponding experiments on full-sized propellers, for if so there would be no object in the model experiments; but rather, that a selected number of experiments should be carried out, here and there over the field of propeller forms and proportions, thus establishing the presumptive degree of accuracy in model experimental work. With such margin of error known, model experiments could be used freely, with suitable corrections if necessary, and the results would then have all the accuracy which can attach to model experimental work corrected by reference to direct experiment on full-sized forms.

So much for the propeller itself. It must be remembered, however, that the propeller is but the connecting link between the prime mover and the aëroplane, and that no matter how excellent the propeller in itself, it must be adapted to the prime mover and to the aëroplane in order to secure a harmonious and efficient combination, or rather all three must be adapted each to the other, and it is in this lack of adaptation that much of the trouble with and inefficiency of the screw propeller in actual use arises. Thus no matter how efficient the propeller itself at a suitable value of the slip, if it is too small for the aëroplane, the slip will become excessive with corresponding loss in efficiency. Again if too large or if the relation between speed of advance, slip and torque are unsuitable, the propeller will perhaps hold down the motor to a rotative speed entirely too low and thus render impossible the development of the desired power. These and other relations are of course well known and are only mentioned here in order to emphasize the importance of the most careful inter-adaptation between the aëroplane, the motor and the propeller.

In this field there is still important work to be done in a more complete study of the characteristics of the aëroplane and propeller separately and when combined in their normal relation, all with a view of insuring a more perfect adaptation of the one to the other and of the prime mover to both.

The air propeller has thus far been normally made of wood and of the two-bladed form. Outstanding problems which are awaiting investigation relate to the best modes mechanically of making three and four blade propellers with the consequent saving of diameter for the same thrust, revolutions and slip; also to the practicability of propellers of light metal alloys instead of wood. Some work has been done along these lines and some hopeful indications have appeared.

A further problem, structually, relates to the thickness necessary for strength under the complex stress due to centrifugal force and air pressure, and also the distortion of the blade under these loads and the extent to which such distortion may modify the geometrical characteristics of the propeller itself.

Concluding we may in resumé sum up for the aëroplane as a whole, the insistent demands on the realization of which future progress must depend. These are:

1. Minimum weight of structure in relation to area of supporting surfaces and of power plant per unit of power developed. This will secure increased carrying capacity for fuel and supplies and for useful weight such as passengers, mail, etc., and this will serve as a factor in either long life in the air or heavy carrying capacity for short distance. On the other hand such extra weight carrying capacity may be put into additional power plant, engine and fuel, for correspondingly increased speed over shorter distances.

2. Maximum economy of prime mover and in applying its power for propulsive purposes. This will insure minimum consumption of fuel and supplies per unit of time or distance, and hence will serve as a factor in long life in the air or in large weight carrying capacity, or in added capacity of prime mover with corresponding increase of speed for shorter distances.

3. Reliability of operation. This embodies improved methods of control and navigation, and greater reliability in each of the many individual elements on which overall reliability in operation depends. These improvements are of special significance in the problem of lengthening the effective life in the air and broadly in the extension of the usefulness of the aëroplane especially in the arts of peace.